Effects of Managed Burning in comparison to vegetation cutting on dissolved organic carbon concentrations in peat soils

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Abstract

Given continuing concern about rising concentrations of dissolved organic carbon (DOC) in stream water leaving peat-covered catchments this study has considered the impact of managed burning or cutting of *Calluna vulgaris,* a dominant vegetation cover in many UK peatlands. The study considered pristine mature *Calluna* stands in comparison to those that had been subject to cutting and or managed burning up to 5 years after intervention. The study measured the DOC concentration of both soil and surface runoff water over a period of 12 months in comparison to water table depth, conductivity and pH. The study has shown that:

i) The depth to the water table decreases upon both burnt and cut sites relative to controls in line with a change in evapotranspiration due to loss of vegetation;

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ii) The DOC concentration of surface runoff water was not significantly different ($p < 0.05$) between any of treatments and the control;

iii) The DOC concentration in soil water significantly ($p < 0.05$) decreased with both burning and cutting but that these differences could be explained by differences in water table and soil water conductivity.

The study suggests that declines in soil water DOC concentration are brought about as different levels in the peat profile become the dominant source as due to changes in water table brought about by changes in evapotranspiration that result from the loss of vegetation. The changes in water table mean that and that this mechanism may explain other observations of DOC concentration change with management. Cutting and burning may represent a management intervention that could be effective at reversing the current trends in DOC transfers from peat-covered catchments.

INTRODUCTION

Increasing concentrations of dissolved organic carbon (DOC) have been observed in Boreal and sub-Boreal regions across the Northern hemisphere. Increases have been observed in North America (Driscoll et al., 2003) and in Central Europe (Hejzlar et al., 2003). For the UK, Worrall and Burt (2007a) have shown that out of 315 catchments studied in the UK, 68% showed a significant increase over timescales of between 9 and 42 years, for catchment areas ranging between 400 m^2 and 9800 km^2. These increases have generally been associated with peat soils (Aitkenhead et al., 1999). Increases are not, however, universal. Skjelkvale et al. (2001) report a mixed picture for lakes in Finland, Norway and Sweden. Equally, although Worrall and Burt (2007b) have shown widespread increases in DOC flux from peat-covered catchments in the UK, they have also shown significant decreases in DOC flux from all the peatlands of south western England.

Increasing concentrations of DOC entering surface water is a cause of concern because it could be indicative of increasing losses of carbon from the vital peatland carbon stores. Furthermore, the concentration of DOC is a major problem for water companies in the UK and parts of Northern Europe, as the removal of DOC from water supplies is one of the greatest costs in the treatment process. Incomplete removal of DOC leads to coloured water which is of low aesthetic quality; it increases the potential for biological contamination by consuming free residual chlorine; and can form potentially carcinogenic tri-halomethanes whose concentration in drinking water is limited by law in the UK (Hsu et al., 2001).

There are several proposed mechanisms to explain the observed increases in DOC. These include: increasing air temperature (Freeman et al., 2001a); changes in pH (Krug and Frink 1983, Lofts et al. 2001); change in the amount and timing of rainfall causing shits in the balance of flowpaths (Tranvik and Jansson, 2002); increases in atmospheric CO_2 concentration (Freeman et al., 2004); changes in atmospheric deposition particularly of S (Evans et al., 2005); occurrence of severe drought (Worrall and Burt, 2004); eutrophication (Harriman et al., 1998) and these could be enhanced by local land management (e.g. Mitchell and McDonald, 1995). It is likely that some or all of these drivers have contributed to increases in DOC concentrations.

Given the consequences of increased losses of DOC from peat soils for carbon storage and water treatment is it possible to manage these changes? It is unlikely that the effects of climate change or atmospheric deposition can be reduced on short timescales (<10s yrs). It would therefore seem prudent to manage these vulnerable environments in order to minimise DOC losses through appropriate land use. Unlike many Boreal and sub-Boreal peatlands the peat soils of the UK uplands are heavily and extensively managed for livestock and recreational shooting. In order to increase productivity managed burning of vegetation has been a common feature of the UK uplands. Up to 40% of English moorland has been burnt with approximately 20% of upland heath and bog in the North Pennines Area of Outstanding Natural Beauty (AONB) having been burnt within the past 7 years (Yallop et al. 2006). Burning is regulated by the UK Department for Environment, Food and Rural Affairs (DEFRA). DEFRA recommends (DEFRA, 2007) that individual burns should; not exceed 2 hectares with a maximum width no greater than 30m (DEFRA, 2007); burning that is no more frequent than once every 12 years; and finally, that burning takes place between 1st October and 15th April. The aim in restricting the period when prescribed burning can take place is to ensure a ‘cool’ burn by not allowing the burning of peat and vegetation during drier, hotter summer months. A ‘cool’ burn aims to remove the vegetation layer without damaging the underlying litter or peat.

The vegetation response to burning is well documented (Mallik and Gimingham 1983; Hobbs 1984; Hobbs and Gimingham 1984). The burning of peatland vegetation promotes the development of grass-dominated communities especially on shorter burning rotations (Hobbs 1984). This vegetation response improves grazing for sheep and is reflected in higher sheep performance on burnt plots (Lance 1983). Grouse production has also been correlated with the density of burnt areas (Picozzi 1968). Clay et al. (2010) estimated the total C budget of plots under a range of burn managements including unburnt controls and showed that while the total C budget on unburnt plots was a source of 156.7 gC m^{-2} yr^{-1} that on burnt plots was total C source was 117.8 gC m^{-2} yr^{-1}, i.e. the study showed that although all plots were net sources of C the burnt plots represented an avoided loss. What, however, are the consequences of managed burning for water quality and especially for DOC?

At the plot scale, Ward et al. (2007) and Clay et al. (2009a) found no significant difference in DOC concentrations in soil waters between burnt and unburnt sites while Worrall et al. (2007) and Helliwell et al. (2010) showed a significant decrease in DOC concentration in soil water on burnt sites, though the latter study was not on a deep peat. Worrall et al. (2007) and Ward et al. (2007) considered the same site and only considered burnt sites 9-10 years after a burn. Clay et al. (2009a) and Helliwell et al. (2010) consider changes after a burn and Clay et al. (2009a) considered pre-burn vs. post-burn. Clay et al. (2009a) is the only study to consider concentrations in surface runoff at the plot scale, and found no significant difference between burnt and unburnt plots, and none of these studies considered stream water DOC concentrations in comparison to measured soil or surface runoff water.

There are also a number of studies at larger scales i.e. catchment scale. Burns more than 4 yrs old, or those on soil types other than blanket peat, show no observed effect on humic DOC in catchment drainage (Yallop et al., 2008; Yallop & Clutterbuck, 2009; Chapman et al., 2010). In total or partly blanket peat catchments, however, Yallop et al. (2008) and Yallop and Clutterbuck (2009) found a significant positive relationship between the area of new burn (typically <4 yrs old) on blanket peat and drainage humic DOC concentration. Using long-term trend analysis, Clutterbuck & Yallop (2010) showed that this relationship explains a much greater fraction of the increase in drainage DOC over the recent past than either increasing temperatures or declines in acid deposition. Yallop et al. (2010) showed that increases in humic DOC concentrations related to new moorland burns on blanket peat represent an increase in loss of carbon, and that areas of new burn (<4 yrs old) on blanket peat show a 5- to 15-fold greater loss of humic DOC compared to areas not burned that recently. However, Chapman et al. (2010) also note increases in DOC concentration in a range of peat-covered, English catchments, including ones where there was burn management, but observed changes were independent of burning and the variation in increase was larger than that observed by Clutterbuck and Yallop (2010), rather magnitude of increase in DOC concentration was greatest in catchments where DOC concentration had been lowest at the start of the period of observation. However, the study of Chapman

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et al. (2010) has recently been debated by both Yallop et al. (2012) and Chapman et al. (2012).

If the evidence of the effect of burning upon DOC concentration is still debated there is evidence that burning can be detrimental in other ways. Wildfires, accidental burns, have been linked to increased peat erosion (Tallis, 1997), also managed burns that get out of control can burn larger areas of vegetation than required. Both can lead to a loss of ecosystem production negating any potential gains had the vegetation been left alone. Moreover, out of control burns can burn into the litter layer and the underlying soil thus releasing carbon that was in long-term storage. Given the potential detrimental effects of burning alternative means of controlling vegetation have been sought. This study, therefore, set out to compare the impact of managed burning over time with the alternative practice of heather cutting to contrast their impacts on peatland hydrology and carbon storage.

APPROACH AND METHODOLOGY

Study sites

The study sites were all situated in the Goyt Valley, Derbyshire, England, an area within the Peak District National Park (Figure 1). The area is a water supply catchment for the city of Manchester and is entirely owned by the local water company. The soils of the valley are dominated by peats and as a consequence rising DOC concentrations are the dominant water quality problem for this supply although there is no long period observations to suggest a trend in water colour or DOC. The peat soils are dominated by *Calluna vulgaris* with some *Sphagnum spp.* mosses in wetter areas. The area is used for sheep grazing but this is light and largely away from the peat soils and wetter patches. The valley has been used for recreational grouse shooting but there has been no managed burning within the catchment for at least 5 years, although an accidental burn occurred in the valley in April 2007.

The experiment is designed to compare the cutting of *Calluna vulgaris* as an alternative to burning this vegetation type. The cutting of *Calluna vulgaris* was performed in two ways: cut and lift; and cut and leave. In both cases the vegetation is flailed to the ground level but in the former case the cuttings are removed from the site with a forage harvester while in the latter the cuttings are left as they fall.

The sites available to the study included: a fresh cut and leave (GS1); a 1-year old cut and leave (MOSS); a 1-year old cut and lift (BEN and GS3); a fresh burn (ob); a 1 year old burn (BN and BS); a 5 year old burn (PROM) and a control (PAT). The control site is typified by mature to degenerate *Calluna vulgaris* with an open structure allowing mosses and lichens to develop. The 1 year old burn treatment was part of an accidental fire that occurred on April 2007. Within the scar of this accidental burn sites were chosen where ground conditions mimicked those of managed burns, i.e. litter still present and no sign of soil scorching, and therefore, the 1 year old burn was taken as equivalent to a managed burn – details are given in Table 1.

Before the start of the experimental burns of *Calluna sp.* were conducted in April 2008. This was beyond the season permitted in the DEFRA Burning Code but the burns were permitted by license of Natural England for our research: two fresh, or new burns were conducted upon the study site. The burning was conducted by local estate staff trained and experienced in conducting managed burns of *Calluna sp*. The treatments were then instrumented as soon after the burns as possible and allowed to settle such that sampling could begin in May 2008. Subsequently sampling took place every month until June 2009.

All the plots were chosen to be in deep peat, i.e. peat of greater than 50 cm deep (Avery, 1980). The size of all plots, except those designated as controls, was consistent with the typical size of prescribed burn plots as set out within the Defra burning code (2007), ie. No more than 150m long by 30m wide. The management plots were sited along a flat ridge of peat which meant that no plot was positioned hydrologically above any other or indeed below anther management.

Monitoring regime

The sites chosen for their particular management were set up so that within each treatment there were duplicated plots and within each plot sampling for soil water and runoff water was triplicated. In some cases the duplicated plots are within the same site but this was not always possible. For example, sites BS and BN are both old burn (1 year) treatments but it was not reasonable for them to be on the same site, and so these plots were placed on different sites of the same treatment (Table 1). Soil water from below the water table was accessed via a series of dipwells from the surface. In each plot three dipwells were placed to at least 90 cm depth with openings along the entire length. Depth to water table and soil water was measured at least once a month.

In addition to the soil water samples, crest-fall runoff traps were installed alongside each dipwell in order to intercept surface flow from the plots. These 20 cm deep by 5 cm diameter upvc pipes were sunk into the peat surface with seals at both ends but with holes at the surface to allow in any surface runoff, holes were aligned with and perpendicular to the local slope. Traps were inspected at least once a month until June 2009 and if water was present it was sampled. The samples were then analysed using the same techniques as for the soil water samples collected from the dipwells. The actual runoff from a plot and a hillside to a catchment will be a mixture of the soil and runoff water compositions sampled by the installed equipment – the implications of the mix of the sampled waters are discussed below.

Water samples from the dipwells were analysed for pH, conductivity, absorbance at 400nm (Abs_{400}), E4/E6 ratio and DOC concentration. Absorbance was measured at 400 nm for a basic colour reading (Thurman 1985). DOC concentrations were measured colorimetrically using the method by Bartlett and Ross (1988). By measuring both absorbance at 400 nm and DOC, specific absorbance can be evaluated and thus the nature of the DOC can be tested. Furthermore, the E4/E6 ratio (the ratio of absorbance at 465 nm to absorbance at 665 nm) was also measured as an additional assessment of DOC composition.

Chen et al. (1977) has shown that the E4/E6 ratio is: (i) mainly governed by the particle size or molecular weight; and is affected by pH: pH of all water samples was included as a covariate in the analysis. The pH and conductivity were measured by electrode methods.

In total the study consisted of 63 dipwells and 63 runoff traps which over the time of the study meant that there was a possible 773 possible observations of each determinand considered in both soil and runoff water. However, due to low water tables it was not always possible to sample soil or runoff water on every occasion.

Statistical Methodology

The sampling survey design used in this study is not a complete factorial with respect to all the factors that could be considered. However, within this design it is possible to consider the statistical significance of the following factors:

Treatment – these are the differences between the cutting and burning treatments which at its maximum had the following levels at the study location.Therefore, as an additional analysis and in order to test whether burning treatments are distinctly different from cutting treatments the treatment levels were amalgamated to just 3: control, cut and burnt.

Month – in order to allow for the difference between sampling days and in order to assess the seasonal cycle the month in the calendar year is included as a factor where: January = 1 and December = 12.

Runoff vs. surface water - the analysis was performed for all measured soil water components (based on samples collected from dipwells) and then separately for the individual measured components in the runoff water samples (samples collected from the runoff traps). However, in separate analysis the soil water and runoff water samples were compared in order to test the significant differences between the two flowpaths across the year and across the treatments.

Appropriate covariate information was used. The magnitude of the effects of each significant factor and interaction were calculated using the method of Winer (1971). Post-hoc testing of the results was performed for pairwise comparisons between factor levels using the Tukey test in order to assess where significant differences lay between factor levels. There are several problems associated with using the general linear modelling approach. Firstly, the Levene test was used to assess the homogeneity of variance with respect to all factors in the general linear model. If a set of data failed the Levene test the data were log-normalised and re-tested for normality – in the case of this study no further transformations proved necessary. Secondly, all significant differences are assessed at the 95% probability of not being zero. Thirdly, the ANOVA should have sufficient statistical power in order not to risk type II errors at a given level of significance: the survey design used in this study was that shown to be effective in Worrall et al. (2007). Fourthly, each plot had a unique treatment (eg. burnt) and no additional treatments were applied to any individual plot within the study period and so a repeated measures design was not required.

RESULTS

Depth to water table

The depth to the water table was measured 437 times. The average depth to the water table on the control site was 44 cm below the surface but on the new cut & leave site the median depth to the water table was 6 cm (Fig. 2) and although each treatment was measured at least 56 times across each month of the year the new cut & leave treatment has a far more restricted range than the control. When comparing all the treatments the difference between them is significant and is the most important factor in the ANOVA (Table 2). The post hoc comparison shows that there is a significant difference between the control and all treatments except with the new burn. In all cases, except that of the new burn treatment, the depth to the water table decreases with treatment. When the data are amalgamated the importance of the difference between treatments increases and post hoc testing shows significant differences between burning and cutting and the controls. The effect of management intervention be it cutting or burning can be explained as the loss of vegetation causes a decrease in evapotranspiration that means water tables can rise. The significant difference between burning and cutting treatments may be explained by a mulching effect of the cut vegetation left upon the soil surface, however, it should be noted that there was no significant difference between the cut and leave treatments and the cut and lift treatments, and thus an alternative explanation of the difference may be due to changes in aerodynamic roughness and surface resistance

Soil water DOC

Soil water DOC was measured in 309 samples with no treatment measured less than 21 times. The median DOC concentration for the control was 142 mg C/l while for the new cut & leave the median value was 96 mg C/l (Fig. 3). The first ANOVA between all treatments shows a significant difference between treatments although it was less important than the month factor or the error term (Table 2). The post hoc analysis shows that the only treatment that is different from the control is the new cut and leave. There were no significant differences between the new burn and any other treatment, but the new cut and leave was significantly different from the 1 year old burn; old cut and leave; and the new cut and lift.

When data are amalgamated the difference between treatments explains only 5% of the variation in the original dataset. The difference observed is between the control and the cut treatments with the average DOC concentration on cuts being 24% lower, though it should be noted that the average DOC concentration for burn treatments was also 22% lower on average but the difference was not significant at the 95% probability.

When covariates are included the difference between treatments becomes insignificant, the two covariates that are found to be significant at least at the 95% probability, and explain the differences previously observed between treatments are the log of the depth to the water table and the conductivity of the soil water samples. The DOC concentration of soil water samples rose with increasing depth to the water table and with increasing soil water conductivity.

Soil water DOC composition

The E4/E6 showed a significant difference between treatments but the post hoc analysis showed that the significant differences were between all sites, including the control, and two, but not all three of the burn sites (Fig. 4, Table 2). The new burn and 5 year old burn were significantly different from all the other sites and in both cases were significantly lower. This view is confirmed when the data were amalgamated and there was a significant difference between the control and the burnt sites but not between the cut sites and the control, however, on average the E4/E6 ratio was lower on the cut sites. No covariates were found to be significant. Therefore, E4/E6 tends to be lower on burnt sites implying that higher molecular weight and more humified DOC being present (Chen et al., 1997).

The specific absorbance was significantly different between treatments (Fig. 5, Table 2) but the difference explains only 10% of the original variance and the pattern of post hoc differences suggests the specific absorbance is following DOC concentration with only the new cut and leave being significantly different from the control and it having a higher specific absorbance than the control. Again when the data are amalgamated there is a significant difference between control and cut sites but not between burnt and cut sites. Moreover the control site has the lowest specific absorbance which is in line with its higher DOC concentration. When covariates are included the log of soil water conductivity is found to be significant and inclusion of the covariates does negate any significant difference between the control and the new cut and leave site. This behaves similarly to differences in the DOC concentration implying that specific absorbance decreases with increasing DOC concentration and does not suggest any compositional differences between treatments with respect to specific absorbance.

Surface runoff water DOC

The DOC of the surface runoff could be measured in 108 cases (Fig. 6, Table 2) with the control being the least represented with 11 samples. There is a significant difference between treatments with respect to the surface runoff DOC concentration but the post hoc analysis shows that no significant differences exist between the control and any of the cut or burnt sites. The significant differences that do exist are between the 5 year old burn and the old cut and leave; and the other burnt and cut sites, but not with the control site. When the data are amalgamated then neither factor is significant, i.e. there is no general difference between burnt or cut sites and the control.

Depth to the water table could not be included as a covariate as the measurement is made on the day of sampling and would not relate to conditions generating the surface runoff. Therefore, only the pH and the conductivity of the surface runoff samples can be used as covariates. Both pH and conductivity are significant and both show a positive correlation with surface runoff DOC concentration. The relationship with pH and conductivity can be interpreted in terms of the source of the surface runoff.

Comparison of surface runoff and soil water

The comparison of the surface runoff and soil water DOC concentrations show that there was a significant difference between sources independent of difference between treatments and the difference between months (Table 2). In this case the soil water DOC was on average 69% of the surface runoff DOC concentration. There was a significant interaction between the type and the month of sampling, i.e. the difference between surface runoff and soil water varies across the year. In fact there were only 5 months where there was a difference between surface runoff and soil water DOC concentration but in 7 months there was no difference, in particular there was no difference in the summer months.

For the DOC composition there was no significant difference between surface runoff and soil water in terms of specific absorbance (Table 2) but there was a significant interaction between type and month. Upon examination this was found to be due to large values of specific absorbance for surface runoff concentrations in September. However for E4/E6 there was a significant difference between types (Table 2) and the E4/E6 was lower in the surface runoff compared to the soil water and there was a significant interaction but it was between the type and treatment factors and not with the month factor. For most treatments the soil water E4/E6 was greater than the surface runoff E4/E6 but for the new burn this was reversed.

Frequency of surface runoff

The proportion of times that surface runoff was detected upon each site was given in Table 3. The values of proportion of detection vary from 10% upto 46%. It was possible to perform a significance test between these measured proportions using the approach of Clay et al. (2009b). This significance test does imply that the there is a significant increase in proportion of surface runoff where there had been management intervention with an approximate doubling of runoff frequency. Such a test could readily be distorted by the nature of each plot, i.e. the slope of one plot under the treatment being different from the slope of another, but this is less true if the comparison is made between management type and in which case there is a significant difference between managed sites (burnt and cut) and control sites. Although there was only a limited number of sites there is no significant correlation ($p > 0.05$) between proportion of surface runoff and the average DOC concentration of the surface runoff at that site, this supports the results of the ANOVA that there was no management effect upon surface runoff DOC concentration.

DISCUSSION

The study has shown a significant effect of cutting and of burning upon soil but not surface runoff water DOC concentrations, why does this occur? There are several lines of evidence from the study that need to be explained. Firstly, there was a decrease in soil water DOC concentrations but not in surface runoff water concentrations; the effect was present for both burning and cutting treatments relative to the control; and the effect decreases or disappears when covariates were included with the proportion of variance explained by the treatment factor decreasing without a decrease in the unexplained variance, i.e. the differences in DOC observed were due in part to differences in the depth to the water table and differences in electirical conductivity of the collected soil water samples. A possible explanation of the observed differences in soil water DOC is that the observed changes were being driven by changes in water table driven by loss of vegetation. The change in the average water table position between control and cut or burnt sites was at least a rise of 8 cm but was 31 cm for cut sites. If the DOC concentration in soil water decreases towards the surface then as the average position of the water table rises it is accessing a lower concentration source of DOC. This view is supported by the fact that surface runoff concentrations of DOC are significantly lower than soil water concentrations, i.e. soil water becomes more like surface runoff as it becomes shallower thus the concentration of DOC drops. This may not only mean that the surface layers of peat are not good sources of DOC but also that higher in the soil profile the water is more likely to be mixed with rainwater and rainwater has a very low DOC concentration – reported ranges of DOC concentration in rainwater vary from 0.82 – 2 mg C/l (Dawson and Smith, 2007). That is, this study does not necessarily need to invoke a change in DOC availability up the soil profile as it can also explain the observation based upon mixing of water sources, a low DOC concentration end-member that represents rainwater and a high concentration DOC end member that represents deep soil water. Evidence for this end-member mixing interpretation comes from the fact that soil water conductivity is a significant covariate for both soil water and surface runoff water DOC concentrations with a positive correlation for each. Soil water that is high in DOC would also be expected to have a high conductivity, conversely, rainwater has a low conductivity and low DOC concentration. Therefore, this study would propose that the declines in DOC concentration observed by this study are not due to changes in production or the composition of the DOC rather it is due to changes in hydrology that mean pathways higher in the peat profile come to dominate and these have a lower available DOC concentration. This explanation of the variation in the observed DOC concentrations does not require a difference in DOC composition and indeed this study suggests that specific absorbance follows the DOC concentration. However, the E4/E6 ratio does show significantly lower values for burnt sites suggesting that there is a distinct effect due to burning distinct from just vegetation cutting. Shifts in DOC composition would have implications for the treatability of the streamwater (Sharp et al., 2008).

Does this hypothesis fit all the observations? Changes in DOC composition are then controlled not by changes in production or solubility but rather the mixing of two sources and the amount of DOC in the sample. Differences between treatments can then be explained by differences in the effect upon depth to the water table but why any one particular treatment affects the depth to the water table in the manner it does is beyond the scope of this study. However, one possible source of difference that this study cannot presently assess is that water table and flowpaths in a particular treatment (eg. cutting) are not just governed by the evapotranspiration from soil or plant surfaces but also by the hydraulic conductivity and porosity of the soil. The hydraulic conductivity of the peat profile at a particular dipwell may well be governed by other physical features such as macropores and soil pipes (Holden and Burt, 2003). Clay et al. (2009b) have measured soil hydraulic conductivies between managed burnt and grazed sites and found variations of between 1.3 x 10^{-8} and 1.4 x 10^{-3} cm/s. Similarly, the porosity of the peat soil, as distinct from its permeability of the peat, could be controlled by the particular management or treatment of a study plot. Therefore differences in the depth to water table could be highly influenced by existence of macropores in the peat that may not be related to management on that site. The balance of flowpaths within and between treatments will be the subject of future research. Further, no ANOVA performed in the above analysis was successful in explaining 100% of the original variance and indeed the error term is the most important term for all the DOC concentration analyses. The error term represents all unexplained variance in the original dataset and is not just the measurement or sampling errors but can represent variation due any factors or interactions that were not or could not be included in the analyses. An obvious factor that could not be controlled within this study were the antecedent hydroclimatic conditions before sampling, i.e. the study can account for seasonal cycles by sampling each month within a year but it cannot account for a rain storm immediately before sampling. Furthermore, the study could not include any sampling prior to management intervention, eg. prior to burning or cutting. Therefore, it could be that the differences observed were differences due to spatial variation across a peat-covered hillside. However, this study was careful to ensure that plots were separated across a single management type, that there is a minimum of six-fold replication within any management type. Equally, the study has provided a consistent explanation of the significant difference observed, i.e. mixing of water types as the depth to water table changes upon management.

Can this proposed explanation account for other studies on the effect of management intervention on DOC concentrations in and from peat soils? The study here was on what normally be considered a dry peat, i.e. the control site has an average water table depth of 44 cm while, for example, Evans et al. (1999) showed that for another intact, UK upland peat soil the water table was within 10 cm of the surface 80% of the year with the maximum summer water table depth being 42 cm. The studies of Clay et al. (2009a and b) were conducted on the same site as the study of Evans et al. (1999), i.e. a site far wetter than one in the present study, and although differences between water tables upon unburnt and burnt sites were significant the average difference was the difference between 13 and 8.7 cm respectively. Therefore, we might propose that the differences in DOC concentration observed by this study were due to changes in the depth to the water table causing changes in source and mixing of the soil water. Such an interpretation suggests that sites that are wetter prior to intervention will see little effect as there are less dramatic changes in the water table that can be achieved or that the baseline is already sufficiently high in the profile that little difference can be made. Studies of drain-blocking have been equivocal with regard to their effect upon DOC concentration – Wallage et al.

(2006) a decline; Worrall et al. (2007b) an increase; and Gibson et al. (2009) no significant change - and this could be because some sites of drain blocking have high water tables despite drainage and others do not.

This study was limited to considering soil water and surface runoff, it did not consider stream water, therefore this study could not demonstrate that the changes observed in this study would lead to decrease in DOC concentrations experienced at a water supply intake in a catchment where cutting or burning had been implemented. The stream water of a catchment will be a mixture of sources within the profile and within the catchment. However, this study has shown that soil water concentrations would decrease upon cutting, that although surface runoff concentrations would not change surface runoff concentrations were always lower than or equal to soil water concentrations and surface runoff frequency increased with cutting. These facts suggest that stream water concentrations would decline. However, if water tables rise under cut sites and runoff frequencies increase it may mean that more water may leave the cut areas than would have left the uncut areas. Thus in a catchment where there are a range of soils this increase in water yield from the areas that produce the most DOC (i.e. peat soils), even if that DOC concentration was lower that what it would have been, could still produce an increase in DOC at a water treatment works intake. However, Löfgren et al. (2010) when comparing plot scale measurements with catchment scale measurements of DOC for sites undergoing recovery from acidification, found that although there was a consistent response at the plot scale to changing acidification there was not a consistent response at the catchment scale. If this were true of management interventions like cutting then the response at the catchment scale could be an increase, a decrease or no change despite what is observed at the plot scale

CONCLUSIONS

The study has shown that both cutting and burning lead to declines in soil water DOC concentration; and increases in surface runoff frequency. Although management intervention brought about no significant differences in the DOC concentration in the surface runoff water the combination of changes brought about by cutting and/or burning will bring about a decline in DOC concentrations in peat-covered catchments. The changes in DOC concentrations were explained by changes in the depth to the water table and by the mixing of differing water sources. Cutting and burning both act to lower DOC concentrations because they cause the water table to rise from its relatively low position. The results of this study could imply that both cutting and burning implemented in such a dry context could have the same effect and reduce DOC concentrations in the streamwaters of a catchment.

References

Aitkenhead, J.A., Hope, D., Billet, M.F., 1999. The relationship between dissolved organic carbon in stream water and soil organic carbon pools at different spatial scales. Hydrological Processes 13, 1289-1302.

Avery, B.W. 1980. Soil classification for England and Wales. Soil Survey of England and Wales, Harpenden. Technical Monograph, 14, 67.

Bartlett, R. J., Ross,D.S., 1988. Colorimetric Determination of Oxidizable Carbon in Acid Soil Solutions. Soil Science Society of America Journal 52(4), 1191-1192.

Chapman P.J., Macdonald, A.T., Tyson, R., Palmer, S.H., Mitchell, G., Irvine B. 2010. Changes in water colour between 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK. Biogeochemistry 101, 1-3, 261-294..

Chapman, PJ., Palmer, SM, Irvine B., Mitchell G., McDonald A., (2012). A response to " Changes in water colour between 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK: a critque of the methodological approaches and measurement of burning management" by Yallop et al. Biogeochemistry (in press).

Chen, Y., Senesi, N., Schnitzer, M. (1977) Information provided on humic substances by E4-E6. Soil Science Society of America Journal 41**,** 352-358**.**

Clay, G.D., Worrall, F. Fraser, E.D.G., 2009a. Effects of managed burning upon dissolved organic carbon (DOC) in soil water and runoff water following a managed burn of a UK blanket bog. Journal of Hydrology 367(1-2), 41-51.

Clay, G.D., Worrall, F., Fraser, E.D.G., 2009b. Hydrological responses to managed burning and grazing in an upland blanket bog. Journal of Hydrology 376, 486-495.

Clutterbuck, B. and Yallop, A.R., 2010. Land management as a factor controlling dissolved organic carbon release from upland peat soils 2: Changes in DOC productivity over four decades. Science of the Total Environment, 408(24): 6179-6191.

Dawson, J.J.C., Smith, P., 2007, Carbon losses from soil and its consequences for land-use management. Science of the Total Environment 382, 165-190.

DEFRA 2007. The Heather and Grass Burning Code (2007 Version). DEFRA.

Driscoll, C. T., Driscoll, K.M., Roy, K.M., Mitchell, M.J., 2003. Chemical Response of Lakes in the Adirondack Region of New York to Declines in Acidic Deposition. Environmental Science & Technology 37,10, 2036-2042.

Evans, C.D., Montieth, D.T., Cooper, D.M., 2005. Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. Environmental Pollution 137, 55-71.

Evans, M.G., Burt, T.P., Holden, J., Adamson, J.K., 1999. Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995. Journal of Hydrology 221, 141-160.

Freeman, C., Evans, C.D., Monteith, D.T., Reynolds, B., Fenner, N., 2001a. Export of organic carbon from peat soils. Nature 412, 6849, 785-785.

Freeman, C., Fenner, N., Ostle, N.J., Kang, H., Dowrick, D.J., Reynolds, B., Lock, M.A., Sleep, D., Hughes, S., Hudson, J., 2004. Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. Nature 430, 195-198.

Garnett, M.H., Ineson, P., Stevenson, A.C., 2000. Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK. Holocene 10, 729-736.

Gibson, H.S., Worrall, F., Burt, T.P., Adamson, J.K., 2009. DOC budgets of drained peat catchments – implications for DOC production in peat soils. Hydrological Processes 23, 13, 1901-1911.

Harriman, R., Curtis, C., Edwards, A.C., 1998. An empirical approach for assessing the relationship between nitrogen deposition and nitrate leaching from upland catchments in the United Kingdom using runoff chemistry. Water Air & Soil Pollution 105, 193-203.

Hejzlar, J., Dubrovsky, M., Buchtele, J., Ruzicka, M., 2003. The apparent and potential effects of climate change on the inferred concentration of dissolved organic matter in a temperate stream (the Malse River, South Bohemia). The Science of Total Environment 310, 1-3, 143-152.

Helliwell, R.C., Britton, A.J., Gibbs, S., Fisher, J.M., Potts, J.M. 2010. Interaction effects of N deposition, land management and weather patterns on soil solution chemistry in a Scottish alpine heath. Ecosystems 13, 696-711.

Hobbs, R. J., 1984. Length of Burning Rotation and Community Composition in High-Level Calluna-Eriophorum Bog in Northern England. Vegetatio 57, 2-3, 129-136.

Hobbs, R. J., Gimingham, C.H., 1984. Studies on Fire in Scottish Heathland Communities .2. Post-Fire Vegetation Development. Journal of Ecology 72, 2, 585-610.

Holden, J., Burt, T.P., 2003. Hydraulic conductivity in upland blanket peat: measurement and variability. Hydrological Processes 17, 6, 1227-1237 .

Hsu, C.H., Jeng, W.L., Chang, R.M., Chien, L.C., Han, R.C., 2001. Estimation of potential lifetime cancer risks for trihalomethanes from consuming chlorinated drinking water in Taiwan. Environmental Research 85, 2, 77-82.

Krug, E.C., Frink, C.R., 1983. Acid rain on acid soil: a new perspective. Science 211, 520-525.

Lance, A. N., 1983. Performance of Sheep on Unburned and Serially Burned Blanket Bog in Western Ireland. Journal of Applied Ecology 20, 3, 767-775.

Lofts, S., Smith, B.M., Tipping, E., Woof, C. 2001. Modelling the solid-solution partitioning of organic matter in European forest soils. European Journal of Soil Science 52, 215-226.

Lofgren, S., Gustafsson, J.P., Bringmark, L. 2010. Decreasing DOC trends in soil solution along the hillslopes at two IM sites in southern Sweden — Geochemical modeling of organic matter solubility during acidification recovery. *Science of The Total Environment 409, 201-210.*

Mallik, A.U., Gimingham, C.H., 1983. Regeneration of Heathland Plants Following Burning. Vegetatio 53, 1, 45-58.

Mitchell, G., McDonald, A.T., 1995. Catchment characterisation as a tool for upland water management. Journal of Environmental Management 44, 1, 83-95.

Picozzi, N., 1968. Grouse Bags in Relation to Management and Geology of Heather Moors. Journal of Applied Ecology 5, 2, 483-488.

Sharp, E.L., Parson, S.A., Jefferson, B., 2006. Coagulation of NOM: linking character to treatment. Water Science and Technology 53 (7), 67-76.

Skjelkvåle, B.L., Mannio, J., Wilander, A., Andersen, T., 2001. Recovery from acidification of lakes in Finland, Norway and Sweden 1990-1999. Hydrology & Earth System Science 5, 327-338.

Tallis, J.H., 1997. The pollen record of Empetrum nigrum in Southern Pennine peats: Implications for erosion and climate change. Journal of Ecology 85, 4, 455-465.

Thurman, E.M., 1985, Organic geochemistry of natural waters. Nijhoff/Junk, Dordrecht.

Tranvik, L.J., Jansson, M., 2002. Terrestrial export of organic carbon. Nature 415, 861-862.

Wallage, Z.E., Holden, J., McDonald, A.T., 2006. Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. The Science of the Total Environment 367, 811-821.

Ward, S.E., Bardgett, R.D., McNamara, N.P., Adamson, J.K., Ostle, N.J., 2007. Long-term consequences of grazing and burning on northern peatland carbon dynamics. Ecosystems 10, 7, 1069-1083.

Winer, B.J., 1971. Statistical principles in experimental design. McGraw Hill, New York.

Worrall, F., Adamson, J.K., 2008. The effect of burning and sheep grazing on soil water composition in a blanket bog: evidence for soil structural changes? Hydrological Processes 22, 2531-2541.

Worrall, F., Burt, T.P., 2004. Time series analysis of long term river DOC records. Hydrological Processes 18, 893-911.

Worrall, F., Burt, T.P., 2007a. Trends in DOC concentration in Great Britain. Journal of Hydrology 346, 3-4, 81-92.

Worrall, F., Burt, T.P., 2007b. Flux of dissolved organic carbon from U.K. rivers. Global Biogeochemal Cycles 21, 1, art. no. GB1013.

Worrall, F., Armstrong, A., Adamson, J.K., 2007a. The effects of burning and sheep-grazing on water table depth and soil water quality in an upland peat. *Journal of Hydrology* 339, 1-2, 1-14.

Worrall F. Armstrong A. Holden J. 2007b. Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. Journal of Hydrology 337, 315-325

Yallop, A.R., Clutterbuck, B., 2009. Land management as a factor controlling dissolved organic carbon release from upland peat soils 1: Spatial variation in DOC productivity. The Science of the Total Environment 407, 12, 3803-3813.

Yallop, A., Thacker, J., Clutterbuck, B., 2006. Mapping extent of burn management in the North Pennines: Review of extent year 2001-2003. English Nature Research Reports No 698, English Nature, Peterborough, UK.Yallop, A.R., White, S.M. and Clutterbuck, B., 2008. Evidence for a mechanism driving recent observed trends in dissolved organic carbon release from upland peat soils. Aspects of Applied Biology, 85: 127-132, Yallop, AR, Clutterbuck, B. Thacker, JI. (2012). Changes in water colour between 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK: a critque of the methodological approaches and measurement of burning management. Biogeochemistry (in press).

Table 1. The details of the site, treatment and number of samples taken for this study.

Site	Treatment	No. of samples
MOSS	New cut and lift	78
GS1	New cut and leave	78
BEN	Old cut and lift	36
GS3	Old cut and lift	39
OB	New burn	78
BN	Old burn (1 year)	36
BS	Old burn (1 year)	36
PROM	Old burn (5 year)	79
PAT	Control	78

Table 2. The proportion of the original variance explained by each factor in the initial ANOVA. a) Comparison with all treatments; b) Comparison with treatment factor degradaed to burning vs, cutting vs. control; c) Comparison of treatments including covariates; and d)Comparison between runoff and soil water concentrations.

a)

	Soil water DOC	Water table	E4/E6	Spec. Abs.	Surface runoff DOC
Treatment	13	69	36	10	22
Month	39	7	15	10	12
Error	48	24	49	80	66

b)

	Soil water DOC	Water table	E4/E6	Spec. Abs.	Surface runoff DOC
Treatment	5	81	14	21	0
Month	61	7	34	19	0
Error	34	12	51	60	100

c)

	Soil water DOC	Spec. Abs.	Surface runoff DOC
Treatment	3	6	12
Month	28	14	7
Log(water table)	2	na	na
Log(cond)	2	23	8
pH			3
Error	65	58	70

d)

	DOC	Spec. Abs.	E4/E6
Treatment	14	1	2
Month	11	12	9
Type	10	0	7
Treat*type	0	0	7
Month*type	8	8	0
Error	57	79	75

Table. 3. The proportion of surface runoff detected on each of the study sites.

Treatment	Proportion of detection
New cut & leave	0.14
New cut & lift	0.27
Old cut & lift	0.38
New burn	0.14
Old burn (1 yr)	0.39
Old burn (5 yr)	0.1
Control	0.14

Fig. 1. The location of the study sites used in this study – for codes refer to Table 1.

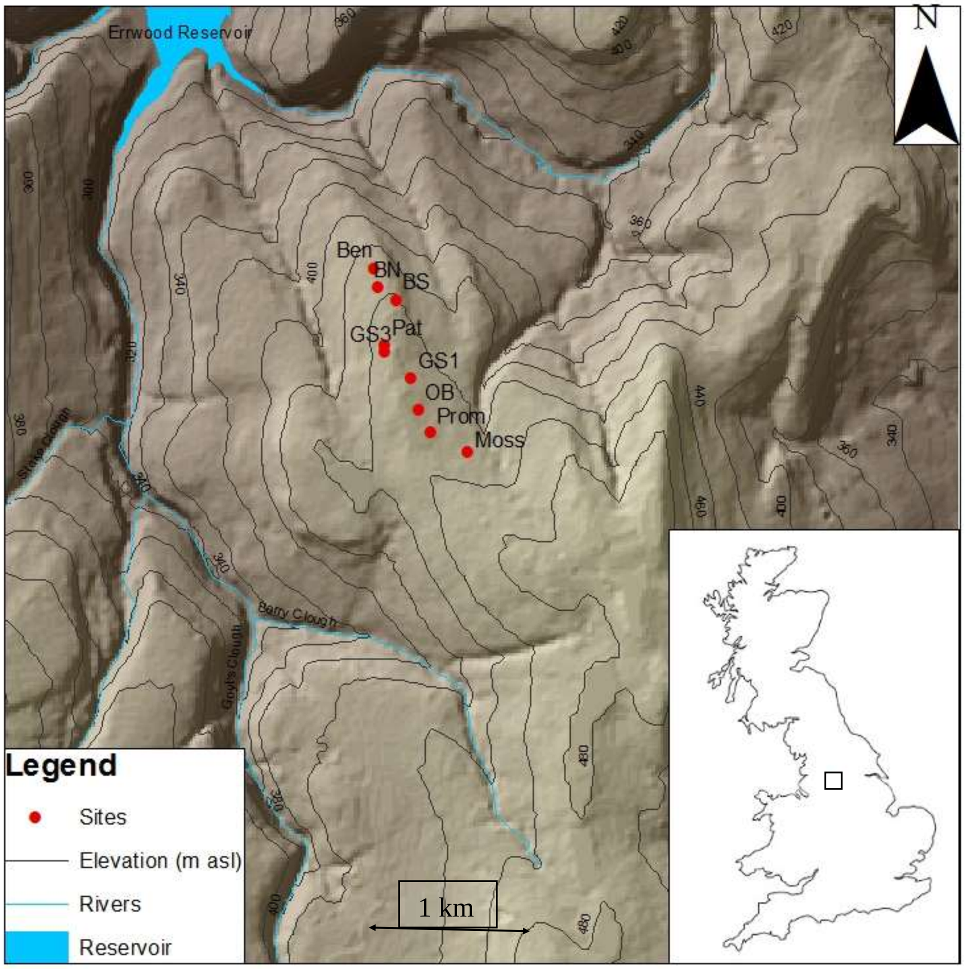

Fig. 2. The box-whisker plot of the depth to water table across the treatments across this study. The box represents the inter-quartile with a median line, the whiskers represent the range of values. (*) indicates a treatment that is significantly different from the control at the 95% probability.

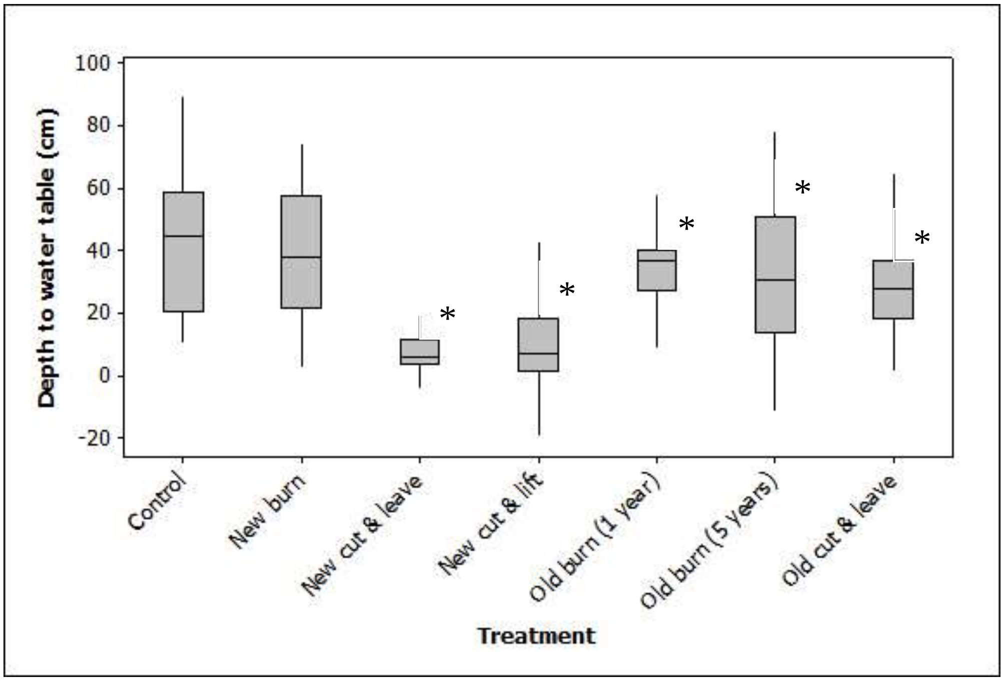

Fig. 3. The box-whisker plot of the soil water DOC concentration across the treatments across this study. The box represents the inter-quartile with a median line, the whiskers represent the range of values. (*) indicates a treatment that is significantly different from the control at the 95% probability.

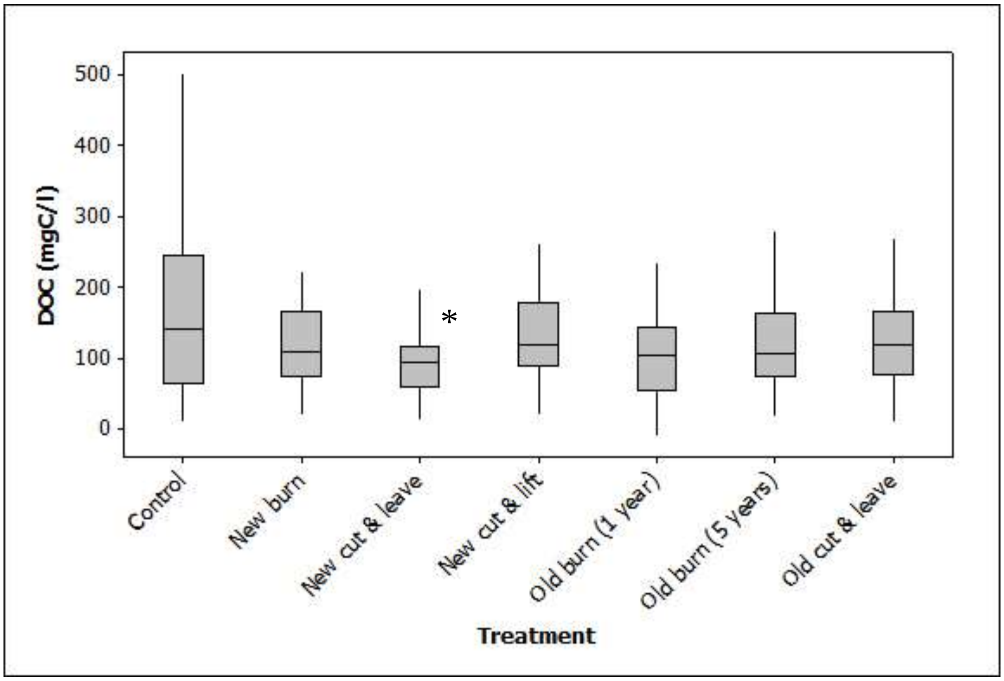

Fig. 4. The box-whisker plot of the soil water E4/E6 across the treatments across this study. The box represents the inter-quartile with a median line, the whiskers represent the range of values. (*) indicates a treatment that is significantly different from the control at the 95% probability.

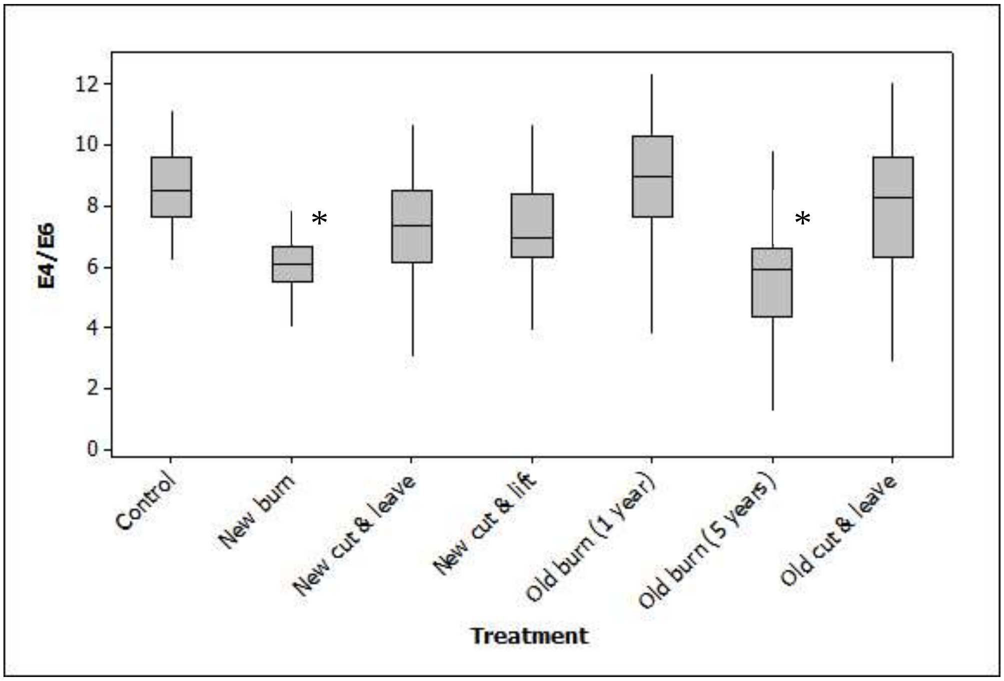

Fig. 5. The box-whisker plot of the soil water specific absorbance across the treatments across this study. The box represents the inter-quartile with a median line, the whiskers represent the range of values. (*) indicates a treatment that is significantly different from the control at the 95% probability.

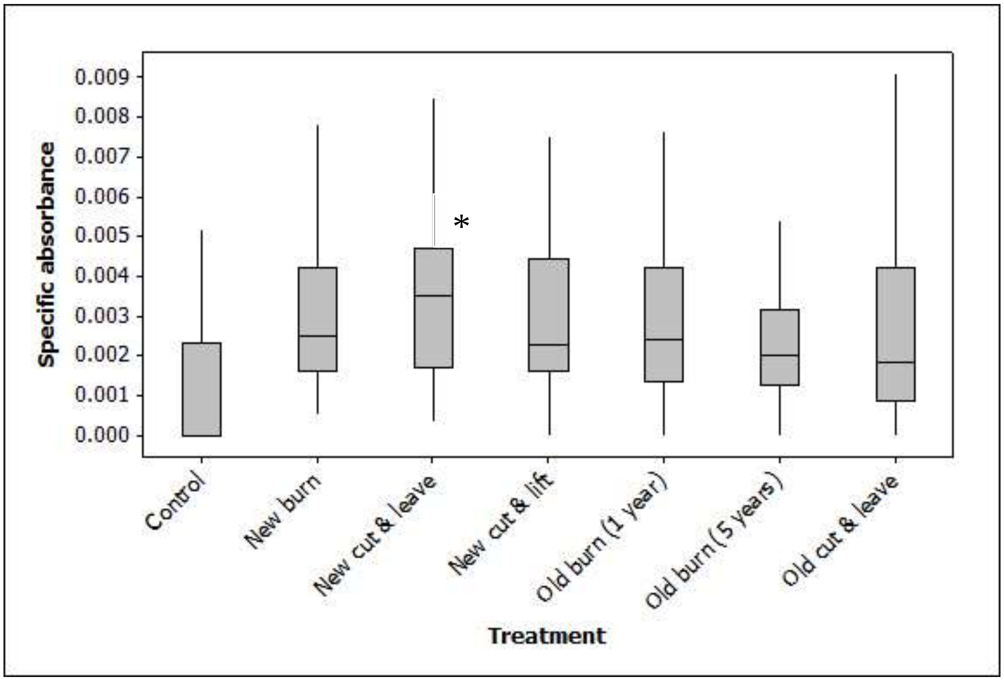

Fig. 6. The box-whisker plot of the runoff water DOC concentration across the treatments across this study. The box represents the inter-quartile with a median line, the whiskers represent the range of values. No significant differences at the 95% probability were found between the control and any treatment.